METHOD AND APPARATUS
FOR EFFICIENT AMPLIFICATION

FIELD OF THE INVENTION

5   The invention relates generally to electronic and electric circuits and, more

particularly, to efficient amplification of signals.BACKGROUND OF THE INVENTION

Traditionally, power amplifiers are categorized into classes. Class A

amplifiers are electrically biased such that the active element of the amplifier (e.g., a

transistor) is always in its linear region (i.e., never completely "on" or "off"). While

10   Class A amplifiers provide high fidelity amplification, they dissipate significant power

because the active elements of such amplifiers must be biased continually, even

when there is no signal input to the amplifier. Thus, the theoretical maximum

efficiency in a Class A amplifiers is very low.

Class B amplifiers involve two active elements in a "push-pull" arrangement,

15   whereby one element drives the output while the other element sinks the output.

Accordingly, when one element is "on", the other element is "off". This arrangement

improves the efficiency of the amplifier; however, when the signal being amplified is

small, there may be times when neither of the elements is active, thereby producing

crossover distortion.

20   Class AB amplifiers combine class A and class B circuitry. A small bias is

supplied to each of the active elements thereby preventing them from being

completely "off". Thus, Class AB amplifiers feature less crossover distortion than class B amplifiers, and less power dissipation than in Class A amplifiers. By virtue of their reliable performance in amplifying high frequency signals, class AB amplifiers are the solution of choice in most low power or high-frequency applications. Still, the

5   energy consumption of Class AB amplifiers is relatively high, as efficiency levels do not exceed 60 percent. Therefore, class AB amplifiers are generally not suitable for high-power applications.

A class D amplifier, as is known in the art, is a switching amplifier that converts a low-level analog input signal into a high power pulse-width modulated

10   (PWM) output. The switching frequency is much higher (at least ten times) the signal frequency, thereby permitting the high frequency components of the output signal to be removed by a simple filter. In a class D configuration, the load is subjected to a full or half bridge of switches, which permit the load to be pushed or pulled, depending on whether the signal is positive or negative. Insofar as the switches

15   dissipate a minimal amount of power, the Class D amplifier is highly efficient, and may reach efficiency levels of up to 97%. Class D amplifiers have typically been used in low frequency (e.g., 20 kHz) and high power applications (e.g., in the kilo-Watts range), such as heavy motor control and high-power audio. The "noisy" nature of class D amplifiers, however, does not lend itself to high frequency/high

20   fidelity applications, where small distortions may have a significant effect.

There are prior art systems and devices that involve amplification of signals of varying frequency ranges. For example, as is known in the art, certain applications of cathode ray tube (CRT) display devices may operate in either or both of two modes. In "sweep mode", low frequency signals are amplified to control an electron beam of the CRT, accounting for most of the power usage of the control system. In "stroke" mode, high frequency signals are amplified for short periods of time, accounting for a small part of the overall power usage. In "stroke on raster" mode, symbols may be scanned onto the display during the vertical retrace period. This mode combines both high and low frequency symbols. To accommodate the high frequency of the "stroke" mode, such CRT devices must use the highly energy-consuming Class A, B or, typically, AB amplifiers. In both modes, the signal is amplified before being applied to the horizontal or vertical yoke to deflect the electron beam.

SUMMARY OF THE INVENTION

Where an application requires amplification of signals in both low and high frequency ranges, or a wide bandwidth and/or at different power levels, as discussed above, the designer generally must choose between using either a class D or a class AB amplifier, thereby sacrificing either fidelity or efficiency. Embodiments of the present invention include an amplifier that can operate in two different ranges of

frequencies, thereby combining the fidelity of class AB amplifiers for high frequencies

with the efficiency of class D amplifiers for low frequencies. According to an

embodiment of the present invention, a circuit is provided that combines the

advantages of these amplifiers. According to another aspect of the present

5   invention, a power supply is provided that supplies substantially constant voltage

irrespective of the current sourced or sinked by the load attached.

BRIEF DESCRIPTION OF THE DRAWINGS

        The subject matter regarded as the invention is particularly pointed out and

10   distinctly claimed in the concluding portion of the specification. The invention,

however, both as to organization and method of operation, together with objects,

features and advantages thereof, may best be understood by reference to the

following detailed description when read with the accompanied drawings in which:

        Fig. 1 is a block diagram of a circuit for amplifying a signal in accordance with

15   exemplary embodiments of the invention.

        Fig. 2 is a schematic diagram of a circuit for amplifying the current of a signal

for an inductive load in accordance with some exemplary embodiments of the

invention;

Fig. 3 is a schematic diagram of a power supply/power controller circuit for driving a cathode ray tube (CRT) deflection device in accordance with exemplary embodiments of the invention; and

Fig. 4 is a schematic graph illustrating the gain of an amplifier in accordance
5   with exemplary embodiments of the invention as a function of signal frequency.

It will be appreciated that for simplicity and clarity of illustration, elements shown in the figures have not necessarily been drawn accurately or to scale. For example, the dimensions of some of the elements may be exaggerated relative to other elements for clarity or several physical components included in one functional
10   block or element. Further, where considered appropriate, reference numerals may be repeated among the figures to indicate corresponding or analogous elements.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

The invention may be used to drive any type of load; however, the
15   configuration of the particular embodiment may vary depending on the nature of the load. Fig. 1 schematically illustrates an amplifier circuit in accordance with embodiments of the present invention. As shown in Fig. 1, a signal may be input into the amplifier circuit at input terminal 100. A signal with frequency high enough to pass through the high-pass filter 110 is amplified by class AB amplifier 130 and out to

output terminal 150. A signal with frequency low enough to pass through the lowpass

filter 120 is amplified by class D amplifier 140 and out to output terminal 150. The

high-pass filter 110 and low-pass filter 120 may, for example, be designed such that

their gain is identical and/or such that the low cut-off frequency of highpass filter 110

5   and the high cut-off frequency of lowpass filter 120 are identical; however, this is not

necessary if the closed feedback loop is employed. The power signals as amplified

by the two amplifiers are mixed at adder 170 and the resulting signal Sout is output to

terminal 150. The output signal is sensed, for example, by its voltage or current at

sensor 160, and fed back to adder 180.

10   Using the feedback loop as shown, the amplification is properly distributed

between the branches such that each branch operates as necessary depending on

the signal frequency. In this way, the entire circuit may operate with a uniform gain

for a continuous range of frequencies. Variations of the basic circuit design of Fig. 1

may be used to amplify a signal supplied to various type of loads, for example,

15   inductive, capacitive and resistive loads. For such loads, the embodiment may be

modified to compensate for phase shift distortion, as described below. It will be

appreciated by those of ordinary skill in the art that the high-pass filter 120 and

low-pass filter 130 may be comprised of multiple components (e.g., resistors,

inductors, capacitors, etc.), or may be comprised of commercially available filters,

20   depending on the desired results. It will further be appreciated that the elements

comprising the high-pass filter 110 and low-pass filter 120 may be placed anywhere

in the circuit and not necessarily in the relation to the class AB amplifier 130 and class D amplifier 140 as shown in Fig. 1.

Circuits according to embodiments of the present invention may be used to drive an inductive load, such as a deflection coil (yoke) of a cathode ray tube (CRT). As is known in the art, a CRT may have a "stroke on raster" mode, which combines both low and high frequency signals. The present invention is therefore particularly suitable for amplifying deflection signals to a yoke in a CRT in that the signal to be amplified may be of high or low frequency. However, it will be apparent to persons skilled in the art that the invention may also be suitable for any other system or device in which signals of varying frequency ranges, or a wide range of frequencies, are amplified to provide more power efficient amplification.

Due to the pulse-width modulation (PWM) output of Class D amplifiers, they are generally considered too "noisy" for use in amplifying CRT deflection signals because even small distortions in amplification in a CRT can cause significant screen "jitter." According to principles of the present invention, the efficiency of class D amplifiers can be used in a CRT by amplifying only signals of sufficiently low frequencies, for which the PWM noise is insignificant. In contrast, for the high frequency signals, a class AB amplifier circuit is used. Thus, the present invention integrates two amplification functions into one device and, therefore, the invention

may also reduce the size and cost of circuitry associated with the device using the invention.

Although the invention is described herein in the context of a dual-mode CRT device, it should be appreciated that the invention may be used in conjunction with

5   any other type of device, system, circuit, etc., where amplification of signals at varying frequencies or wide bandwidth may be needed. Moreover, the principles of the invention may be used to amplify signals having different ranges of power.

In a CRT stroke on raster scan, the frequencies of both the horizontal and/or vertical deflection signals may vary dramatically, depending on the mode of

10   operation. Thus, an embodiment of the present invention may use a class D amplifier to amplify deflection signals at both low frequencies, e.g., for "sweep" mode deflection signals at frequencies on the order of approximately 15 kHz and 50-60 Hz, and a class AB amplifier to amplify high frequencies, e.g., for "stroke" mode deflection signals at frequencies on the order of approximately 100-2000 kHz.

15   Fig. 2 schematically illustrates an amplification circuit in accordance with embodiments of the invention. Thus, for example, a circuit similar to that shown in Fig. 2 may be used for each of the horizontal and vertical deflection signal amplification circuits of a CRT. The characteristics of the elements chosen may vary depending on the different expected frequencies of the deflection input signal and on

20   the desired power gain. Moreover, some circuit components may be added or

omitted as necessary for a particular application. It should be appreciated that the

applicability of the circuit of Fig. 2 is not limited to CRT applications, and similar

circuits may be used in conjunction with any other application where signal

amplification based on frequency discrimination may be advantageous. Other

5   applications where such a circuit may be useful include but are not limited to wide

bandwidth magnetic deflection devices, wide bandwidth scanning machines, wide

bandwidth power supplies, wide bandwidth motors, valve and actuator controls, wide

bandwidth reactive load drivers, high speed active magnetic bearings, high speed

MRIs, wide bandwidth vibration cancellation machines, wide bandwidth power

10   transducers, high power high efficiency low distortion audio amplifiers, high efficiency

sonar transducer drivers, high efficiency high sped/power LED-diode excitation

circuits, high efficiency noise cancellation circuits, etc. The diagrams and

explanations of the embodiments described herein are not intended as limitations on

the scope of the invention.

15   The circuit according to the embodiment of Fig. 2 receives an input signal at

terminal 302 and produces a uniformly amplified, high-fidelity output signal at the

CRT yoke or deflection coil 336. As explained below, by virtue of the current

feedback arrangement shown, a signal of low frequency or DC is amplified

predominantly through the class D amplifier 318, whereas a signal of high frequency

20   is amplified predominantly through the class AB amplifier 312. In addition, the circuit

as shown ensures that the gain at the CRT is substantially constant regardless of whether one amplifier or the other, or both, is in operation.

To accomplish these and other goals, the circuit may be equipped with an error amplifier 306. The error amplifier 306 receives an input responsive to the sum

5   of the current passing through resistor 304 and the current passing through resistor 332 and capacitor 352 (representing the output signal to the CRT 336, which is 180° out of phase with the input signal). In order to improve the efficiency of the circuit, the resistance of resistor 334 may be decreased and an operational amplifier 350 may be added. The sum of these currents, representing the error of the amplification

10 (using the sum of the class D and class AB amplifiers) is amplified by error amplifier 306.

The signal output from error amplifier 306 is diverted to the class D or class AB amplifier subcircuit, or a combination of both, based on its frequency. Thus, if the deflection signal is of a sufficiently high frequency, e.g., greater than frequency f1,

15 the signal will be amplified by a class AB amplifier 312. Resistor 310 and a capacitor 308 are arranged in a high-pass arrangement according to principles known in the art. Frequency f1 is the frequency for which the current output from the class AB branch is equal to the output of the class D branch. At frequencies greater or less than f1, the two branches operate together in a ratio of current outputs determined by

20 the signal frequency. The components that determine frequency f1 include 310, 348,

314, 316, 320, 326 and 308. High impedance elements 348 and 326 are added to the branches in order to add the currents from the two branches together. Capacitor 362 may be added in parallel to inductor 326 as a trap for the modulating frequency of the class D amplifier, thus reducing output noise of the amplifier. Components 324 and 338 may be used to stabilize the class D branch at higher frequencies.

In an exemplary embodiment of the present invention, the components may have the following values: capacitor 338 may be for example 100 nF; resistor 324 may be 5Ω; resistor 310 may be 10kΩ; resistor 348 may be 5Ω; capacitor 314 may be 1 µF; resistor 316 may be 12kΩ; capacitor 320 may be 100pF; inductor 326 may be 10µH; capacitor 308 may be 10nF; inductor 344 may be 1.5 µH; capacitor 346 may be 80nF; resistor 328 may be 175 Ω; capacitor 330 may be 0.1 µF (assuming for example, a 20µH yoke); resistor 342 may be 10kΩ; capacitor 340 may be 0.1 µF; capacitor 360 may be 150 nF; capacitor 352 may be 30 pF; resistor 334 may be 0.1 Ω; capacitor 362 may be 1.5 nF; and resistor 332 may be 1 kΩ. While the characteristic values of most of the components listed above may be varied by approximately an order of magnitude, the value of two components should be specified more precisely, namely, resistor 334, resistor 332 and resistor 304.

Thus, in the above configuration, any high frequency input signal is amplified predominantly by the class AB amplifier 312, and any low frequency input signal is amplified predominantly by class D amplifier 318. After amplification by either class

amplifier, the amplified signal is received at the CRT deflection coil 336, and sent to ground via resistor 334. This current is sampled as part of the feedback loop to the error amplifier 306. If an operational amplifier 350 is used, its gain multiplied by the resistance of resistor 334 represents a new, typically higher, effective resistance

5   It should be noted that when the load being driven, e.g., the CRT deflection coil 336, is inductive, its increased impedance at higher frequencies introduces phase shift distortion. This phase-shift error should be corrected at those high frequencies. This may be done, as shown in the embodiment of Fig. 2, by resistor 328 and capacitor 330, as well as by capacitor 340 and resistor 342. These

10   elements, in combination, function to correct the phase shift distortion that may be introduced at higher frequencies. Due to the high impedance of the capacitors at low frequencies and DC voltages, the phase-shift correction components do not affect performance at low frequencies. The function of optional switch 364, capacitor 366 and resistor 368 is discussed below with regard to shifting the cut-off frequency of the

15   amplifier.

The combination of resistor 324 and capacitor 338 provide low impedance at high frequencies, thereby diverting current from inductor 326, stabilizing the class D subcircuit 358 at such high frequencies, and limiting the contribution of class D sub-circuit 358 to the current at the deflection coil 336. Likewise, resistor 348 and

20   capacitor 314 provide high impedance at low frequencies, thereby decreasing current

from class AB subcircuit 356, stabilizing the class AB subcircuit 356 at low frequencies, and limiting the contribution of class AB sub-circuit 356 to the current at the deflection coil 336.

The horizontal deflection signal requires retrace of the electron beam at a high rate (i.e., high retrace ratio) and a high current that is typically beyond the capabilities of the overall amplifier configuration due to present technological limitations. Therefore, in an amplifier circuit used to amplify the horizontal deflection signal, switches 352 and 354 may be inserted to prevent the amplifiers from such overload. During normal operation, switches 352 and 354 are closed; however, during rapid retrace, the switches are open and capacitor 360 is charged, creating a half-sine wave at a frequency determined by the characteristics of capacitor 360 and deflection coil 336. Switch 354 helps minimize power loss during retrace. The action is similar to a pendulum, in which the power stored in the deflection coil at the end of a line scanned serves to return the electron beam approximately back to the starting point. This technique is known and used in nearly all televisions produced today.

Parasitic capacitances around error amplifier 306 cause a reduction in the drop-off frequency of the overall circuit, f2 and increase instability in the circuit. Therefore, capacitor 352 may serve to compensate and restrain this tendency to instability created by the parasitic capacitances.

Inductor coil 344 and capacitor 346 operate as a lowpass filter to eliminate

the modulation frequency of the class D amplifier. Those of ordinary skill in the art

will appreciate that the components should be chosen so as not to narrow the

bandwidth of the amplifier. As these components transmit great amounts of power in

5   short periods of time, they should preferably be high quality components, such as

NPO/COG capacitors.

In an embodiment of the present invention, the current passing through

resistor 334 represents the sum of currents put out by both the amplifier branches,

which is fed back to error amplifier 306 serving the entire circuit operating as a whole.

10   The result of the feedback loop taking its input from the two amplifier branches is a

unified closed circuit that operates as one amplifier with an overall gain.

The class D amplifier may operate in a full bridge or half bridge configuration.

In a full bridge configuration, one power supply suffices to provide the amplifier with

power; however, the power required to activate the switching elements in this

15   configuration tends to decrease the overall efficiency of the amplifier due to the use

of two pairs of switching elements. In a half bridge configuration, it is convenient to

have both positive and negative power supplies connected to the amplifier. In a full

bridge configuration, however, the power required to activate the switching elements

tends to decrease the overall efficiency of the amplifier.

In order to utilize the class D amplifier in the manner described above, any
power supply adequate for the class D amplifier may be used. One power
supply/power controller circuit that may be used to supply a steady voltage relatively
irrespective of the current being sourced or sunk is described in Fig. 3. One purpose
of the power supply described in Fig. 3 is to convert a floating voltage (Vcc) into
positive and negative voltages relative to a ground. Preferably, each of these voltage
sources, i.e., positive and negative, should be able to supply current and receive
excess current without varying its voltage. In addition, preferably, excess current to
one voltage supply does not become wasted, e.g., become dissipated as heat, but
rather is passed through to charge the other voltage supply, thereby optimizing
efficiency.

In Fig. 3, the voltage divider comprised of resistors 408 and 410 divides the
floating DC voltage Vcc at terminals 400. The PWM controller 402 may operate to
open and close switches 404 and 406, such that the two are never closed
simultaneously. By connecting the end of inductor 412 opposite to the PWM
controller to ground, and tapping the voltage opposite capacitors 414 and 416, stable
voltages relatively irrespective of current sourced or sinked may be obtained at
terminals 418 and 420. Specifically, if the current across capacitor 416 becomes
greater than the current across capacitor 414, capacitor 416 discharges while the
voltage potential between terminals 418 and 420 remains constant Vcc. Thus, as the
voltage across 414 tends to increase, the voltage divider comprising resistors 408

and 410 alters the duty cycle of the PWM controller such that switch 404 is closed for longer durations, thereby compensating for the imbalance. As capacitor 414 discharges, inductor 412 is charged. When switch 406 is closed, the charged inductor discharges across capacitor 416. Thus, the charge stored across capacitor 414 is transferred to capacitor 416 using inductor 412 and switches 404 and 406. The theoretical basis for the efficiency is that the energy across one capacitor, i.e., $CV^2/2$, is transferred to the inductor, i.e., $LI^2/2$, and then to the other capacitor. Thus, the difference between the voltages at terminals 418 and 420 is Vcc. The duty cycle established by the PWM controller determines the values of Vpos at terminal 418 and Vneg at terminal 420. The embodiment of the power supply described provides a substantially constant voltage for power within an operating range.

In an exemplary embodiment of the present invention, PWM controller 402 may be a commercially available controller for a class D amplifier; inductor 412 may be 10µH; capacitors 414 and 416 may be 100 µF; resistors 408 and 410 may be 10kΩ.

In the embodiment shown in Fig. 2, a half bridge was chosen due to considerations of efficiency and simplicity. Thus, positive and negative power supplies are provided that need to work in both source and sink mode. It will be appreciated by those of skill in the art that alternatively, a full bridge or other configuration may be employed with similar effect in accordance with the present

invention. Alternately, those of skill in the art will recognize that a full bridge may be used, accompanied by appropriate alterations in the circuitry.

It will be appreciated by those of skill in the art that a circuit for amplification of both horizontal and vertical deflection signals may be constructed by combining

5   two circuits such as shown in Fig. 2, one for each input signal (Xin and Yin) and each having a separate output signal across the appropriate yoke or deflection coil (Xout across the horizontal deflection coil and Yout across the vertical deflection coil). In such a configuration, both class D amplifiers may be controlled by a single power supply/power controller as shown in Fig. 3.

10 The resultant overall gain of the amplifier of Fig. 2 is illustrated schematically in Fig. 4. The amplification of the subcircuit containing the class D amplifier is shown by curve 500, where f1 is the frequency at which the amplification by the class D subcircuit is halved. The amplification of the subcircuit containing the class AB amplifier is shown by curve 502, where f1 and f2 are frequencies at which the

15 amplification by the class AB subcircuit is halved. Thus, a signal having frequency up to f1 is amplified predominantly by the class D sub-circuit, whereas a signal having frequency between f_1 and f_2 is amplified predominantly by the class AB sub-circuit. The sum of the amplification of the two sub-circuits is shown by curve 504. It will be appreciated that the arrangement shown in the above embodiments

20 result in substantially constant gain regardless of whether amplification is performed by the class AB or class D subcircuits, or both. Moreover, at and around frequency

f_1, the overall gain of the entire circuit is a constant Ao even though both sub-circuits are in operation.

In some embodiments of the present invention, it may be desirable to shift the cut-off frequency for certain applications, for example, in order to narrow the bandwidth of the amplifier. In such embodiments of the present invention, therefore, the cut-off frequency may be shifted, for example, from f2 to lower frequency f2', as shown in Fig. 4, thereby narrowing the bandwidth of the amplifier. This may optionally be accomplished, for example, as shown in Fig. 2, by placing an impedance, such as resistor 368 and capacitor 366, in parallel with capacitor 340 and resistor 342. In an exemplary embodiment of the invention, this additional impedance may be selectively connectable, for example, by switch 364, which may control shifting cut-off frequency f2 to f2'. In an embodiment of the invention, the additional impedance may optionally be altered to variably adjust the cut-off frequency.

While the invention has been described with respect to a limited number of embodiments, it will be appreciated that many variations, modifications and other applications of the invention may be made.

Embodiments of the present invention may include other apparatuses for performing the operations herein. Such apparatuses may integrate the elements of the amplifiers discussed, or may comprise alternative components to carry out the